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Some simplified theories about mass fires

by A.M. Western

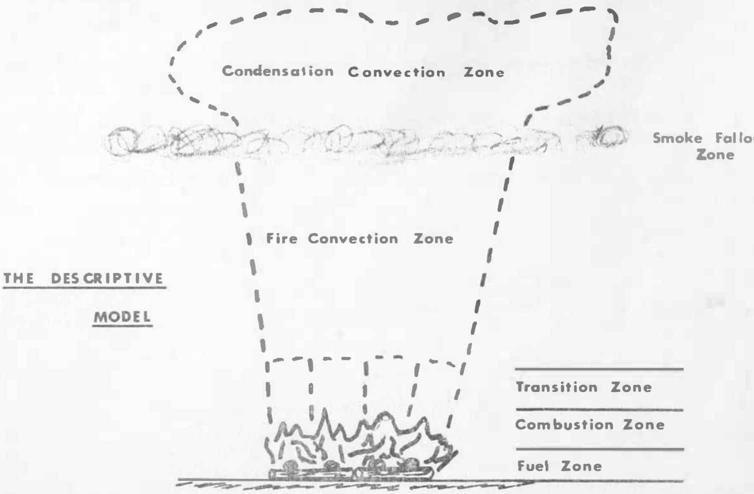
Introduction

In connection with Project FLAMBEAU it was thought useful to make a collection of simple theories relating to mass fires. The list is far from exhaustive; in particular attention has been concentrated on the conditions at peak; with ignition, growth and spread being neglected. Plume theories have also been neglected, as being too complex; Thomas' Working Notes on Project Flambeau (1) give a survey of them. Null hypotheses have been stressed. The prediction of burning rate in a Flambeau type situation is regarded as the central problem, although later sections do cover theories related to shelter and measurements.

The Descriptive Model-Clive Countryman (2)

1 In terms of height:

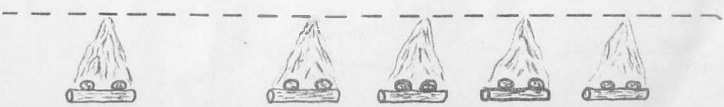
Fuel Zone
Combustion zone-up to perhaps 100'
Transition zone - with some down drafts - up to at most 200' - this is the upper limit of downward influence
Thermal convection zone - up to 1000' - 20,000'
Smoke fallout zone - a thin layer
Condensation convection zone.



Theories of pile interaction

2 At peak intensity, piles do not interact.

2a The burning rate of a pile (b) is not affected by other piles, and is proportional to the surface area of fuel exposed.



ALL BURNING AT THE SAME RATE

2b An isolated pile exposed to standard met. conditions will burn at a rate b (0,t) varying with time t. The reasons for this variation are the initial spread of fire through the pile and the variation in the surface area exposed as the smaller twigs are consumed.

b is better expressed as a function of the total amount burnt:-

$$I = \int_0^t b \, dt.$$

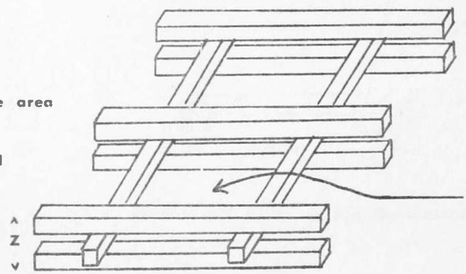
Thus the standard burning rate becomes b (0,I). If the actual burning rate is b(t), then part of its variation is due to the above causes. Put b'(t) = b(t)/b (0,I)

Then the variation of b'(t) with time is mainly due to variation of interaction effects.

2c Pile interaction is by ignition or re-ignition (i.e. spread from pile to pile), in the case of close spacing under poor burning conditions.

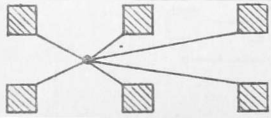
2d According to Thomas (3) the burning rate of a crib or pile in still air is proportional to $Z^{0.6} (A_v A_s)^{0.4}$,

where A_s = Surface area of fuel A_v = Total vertical vent area
Z = Height of pile



3 Piles produce their effects on the environment independently

3a The environment at a point is the sum of that from each of the piles, each at the appropriate distance and burning at the appropriate rate.



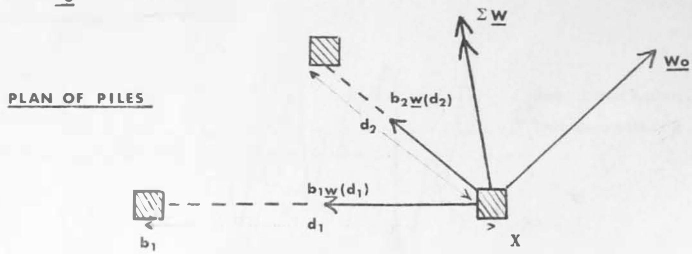
3b The contribution from a pile is proportional to its burning rate.

3c The contribution from a pile at distance d is proportional to $1/d^2$

4 Pile interaction is by means of the wind generated.

4a A single pile burning at a rate b produces a wind $b.\underline{w}(d)$ directed towards itself at a point distance d. In an array a pile has acting on it a total wind $\underline{W} = \underline{W_0}$ + sum for other piles $(b.\underline{w})$

Where $\underline{W_0}$ is the ambient wind.



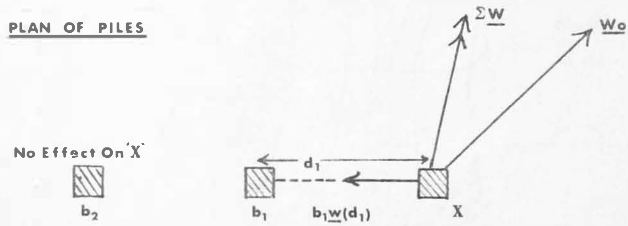
Now the burning rate b depends on $\underline{W}$:-

$$b = b(|W|)$$

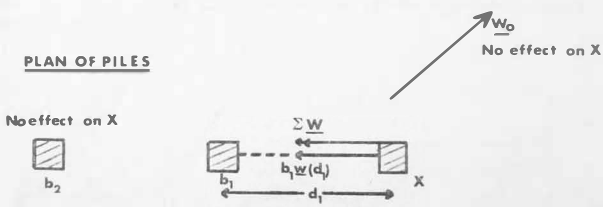
Hence feedback

Moreover, if at a pile directly downwind of the array $\underline{W}$ is acting inwards this is a non-spreading fire; if outwards a spreading one.

4b As theory 4a, but only the nearest ring of piles affect sum $(b.\underline{w})$; all the rest are shielded. Hence only piles on the edge of the array burn at a rate different from $b(W_0)$.



4c As theory 4b, but W
at a rate b(0). -



4d As theory 4a, but determine $\underline{w}(d)$ experimentally in the presence of inert obstacles representing the other piles (in practice the actual other piles might be used, but not ignited and kept well damped down).

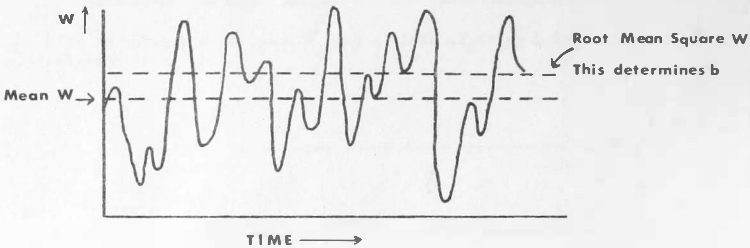
4e As in theories 4a - 4d, but allow also for the variance of the wind and its effect on the burning rate. Assume that the variance of a wind component $b.\underline{w}$ is $u\, b\, |w|$, where u is a constant

The total variance = $G = u \left(W_0 + \text{sum for other piles } (b.|w|) \right)$

Also $b = b\ (|W|)$ can be written as:-

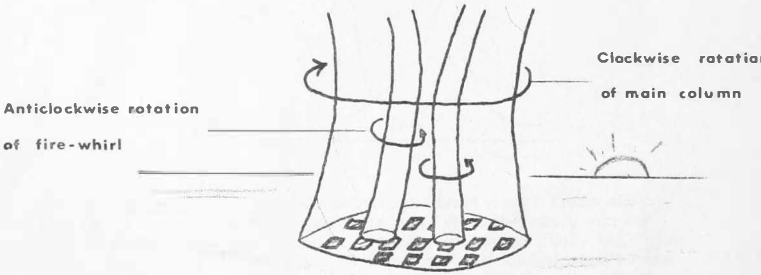
$$b = b\ (W^2)$$

Now expectation of $W^2 = W^2 + G$

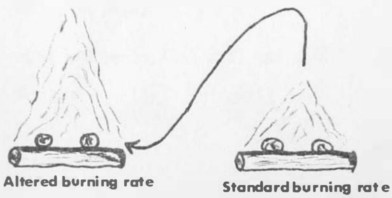


so put $b = b\ (W^2 + G)$.

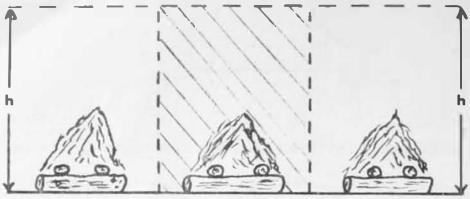
4f The total angular momentum is zero; if there is, say, a general clockwise swirl about the array, its angular momentum will be balanced by anticlockwise fire whirls



5 When a proportion of the draught for one pile is combustion products from the others, this will affect the fire because of the decreased oxygen and the increased temperature

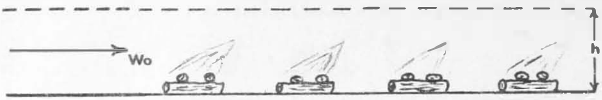


5a Low level air up to some height h is readily available in the central area of a mass fire. If this is sufficient to burn up all the fuel there will be no important interaction. With a fire loading l cals/cm^2 needing a column of air $\frac{l}{k}$ cms. high, this means $\frac{l}{k} \leq h$; if not vertical convective circulation will set in bringing air from above.

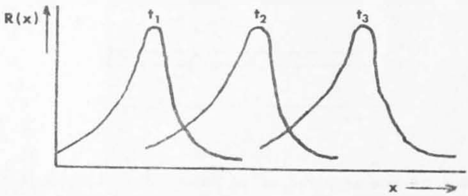


No interaction until shaded air has been exhausted

5b With an ambient wind speed W_0 and a width of array L the volume of air available/sec is W_0 Lh.



Hence the burning rate is $khLW_0$ cals/sec. and thus the rate of advance of the fire front will be $khLW_0/lL$ cms/sec = khW_0/l cms/sec.

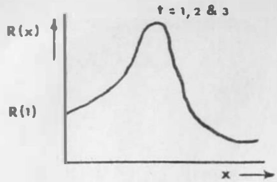


5c As in theory 5b, let air concentration (fraction of fresh air by volume) be c, the burning rate/unit area R(c) cals/cm^2/sec., and the burning efficiency e(c). Then 1 c.c. of air, given the fuel, will give ke(c) cals. (e(1) = 1). Consider the area near the upwind edge of the array, where the ambient wind is the dominant air supply, and assume equilibrium conditions, so that R does not vary with time. Then heat generated/unit area = R = $hW_0(-\frac{dc}{dx})$ e(c) k where x = distance from upwind edge of array.

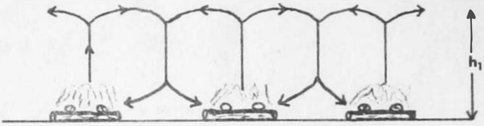
therefore $\frac{dc}{dx} = \frac{-R(c)}{hW_0 ke(c)}$

Solve this for c(x) and hence find R(x) and e(x)

In particular, for x = 0, $\frac{(dc)}{(dx)_0} = \frac{-R(1)}{hW_0 k}$



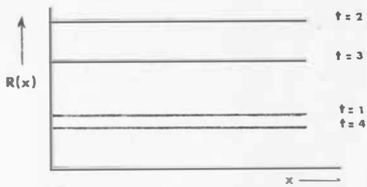
5d Assume air is only available by vertical convection (see theory 5a).



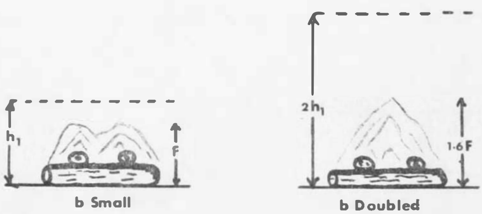
If it is available up to height h_1, then for a vertical prism of air of height h_1 and unit cross-sectional area, heat generated/sec =

$h_1\left(\frac{-dc}{dt}\right) \quad k\, e(c) = R \qquad$ and $\frac{dc}{dt} = \frac{-R(c)}{h_1 k e(c)}$

As before, this can be solved for c(t) and hence for R(t) and e(t).



5e As in theory 5d, but assume h_1 is proportional to the burning rate, or $h_1 = h_0 R$ (h_0 is a constant).



Hence as R builds up to a maximum, more and more fresh air is entrained at the top. While this is happening,

$$ch_1 + 1.dh_1 = (c + dc)(h_1 + dh_1)$$

therefore

$$dc = \frac{dh_1}{h_1}(1 - c)$$

and an extra term must be added to $\frac{dc}{dt}$, giving

$$\frac{dc}{dt} = \frac{-R}{h_1 ke} + \frac{1}{h_1}\frac{dh_1}{dt}(1 - c)$$

$$= \frac{-1}{h_0 ke} + \overline{R}\ \overline{dt}$$

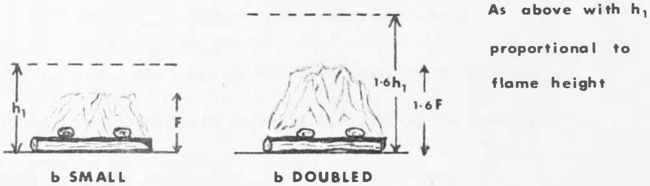
Put $\frac{dR}{dt} = \frac{dR}{dc} \cdot \frac{dc}{dt}$; we have:-

$$\frac{dc}{dt} = \frac{-1}{h_0 ke(c)\left(1 - \frac{1}{R(c)}\frac{dR}{dc}(1-c)\right)}$$

After the maximum there is no further entrainment and the extra term should not be added,

hence $\frac{dc}{dt} = \frac{-1}{h_0 ke(c)}$

5f As above, but h_1 is proportional to the flame height F.



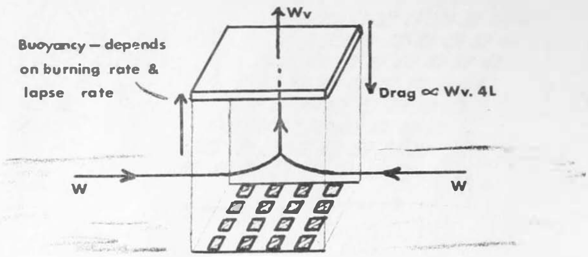
If theory 7b is valid in these circumstances F is proportional to $R^{2/3}$. Put $h_1 = h_0 R^{2/3}$

Then, before peak intensity, $\frac{dc}{dt} = \frac{-\{R(c)\}^{1/3}}{h_0 ke(c)\left(1 - \frac{2}{3R(c)}\frac{dR}{dc}(1 - c)\right)}$

and after, $\frac{dc}{dt} = \frac{-\{R(c)\}^{1/3}}{h_0 ke(c)}$

5g For $\underline{W_0}$ in theories 5b and 5c substitute $\underline{W_0} + \underline{W}$, where W is given by $\underline{W} = .16 W_v \sqrt{\rho_{plume} / \rho_{air}}$, acting towards the centre of the array. W_v is the upward velocity of the plume - Thomas (4).

Now drag force per unit height on plume is proportional to W_v. Perimeter 4L. Assume this is equal, or at least proportional, to the buoyancy force per unit height; and that this is a linear function of b' and the difference between the atmospheric lapse rate and the adiabatic lapse rate (where b' = total burning rate = sum (b) = R
N.B. since buoyancy is proportional to L and drag to L, W_v is proportional to L and there must be an area effect.



Also $\rho_{plume} = c\rho_{air} + (1-c)\rho_{flame}$

And $c = \dfrac{\text{Volume of excess air}}{\text{" " " " + volume of flame}}$

With Volume of excess air = 4LhW - b'/ke

and Volume of flame $= \dfrac{b'}{ke} \cdot \dfrac{\rho_{air}}{\rho_{flame}} \cdot$ stoichiometric ratio

Alternatively, assume the burning rate is a function of $|\underline{W_0} + \underline{W}|$

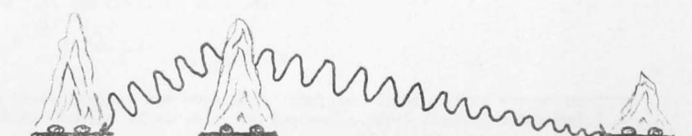
(cf theory 4a). In either case there is feedback on the burning rate.

6 Thermal radiation feedback

Burning rate $b = b_0 + b_1 S$

Where S = solid angle of flame and burning fuel
= S (piles) + S (other flames)

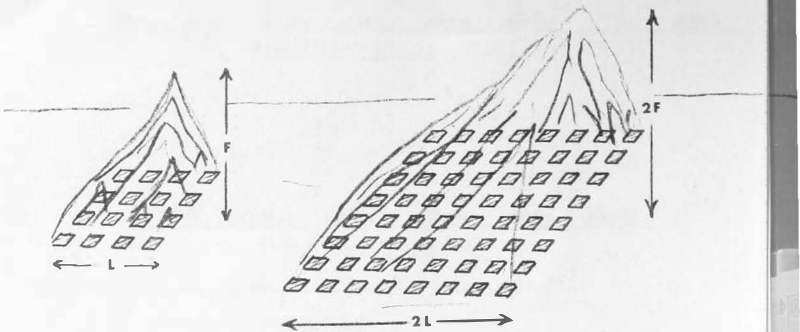
Also S (flame) = S(b) - hence feedback.



Theories of Scaling

7 Flame height scaling

7a Flame height F proportional to linear dimensions L.
Already falsified by trials - Craig Chandler



7b From Thomas (4), F/L is usually proportional to the cube root of R^2/L (note: this is a similar result to theory 9b below with n = 2½). Other regimes are possible, but it is always a function of R^2/L.

Therefore $F = a\,(RL)^{2/3}$ (where a is a constant).

Let piles be U cms square, with gaps of V cms between them.

Then flame height for isolated pile $= F_1 = a\, b^{2/3}\, U^{-2/3}$

And if the flames from N piles have merged, the new flame height,

$F_2 = a\, b^{2/3} N^{1/3}\, (U + V)^{-2/3}$

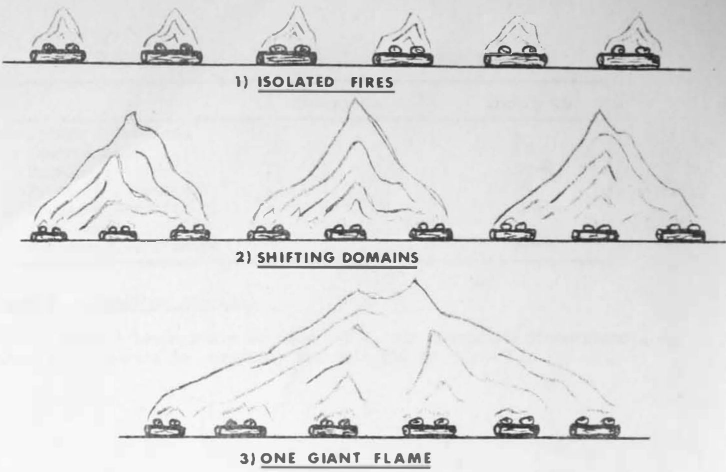
Now assume that isolated fires will join if $F_1 > iV$ and that a merged "domain" of N fires will persist if $F_2 > j\,N^{1/2}(U + V)$, where i, j are numerical constants, perhaps of the order of 1. (Thomas, Baldwin and Heselden's results (5) suggest that i is not constant, but is in the region of 5-7 in a Flambeau situation.)

These correspond respectively to the ratio of the flame height to the gap, and to the dimensions of the domain.

Assuming that these two conditions occur simultaneously, the ratio of flame heights on either side of the discontinuity, (i.e. that with domains of 2 fires just not breaking down, divided by that with isolated fires just not merging) will be:-

$$2^{1/2}\,\frac{j}{i}\,\left(\frac{U + V}{V}\right)$$

Thus three regimes are possible: isolated fires, fires merged to give shifting domains of about N, or the whole array forming one giant flame.



In the partial merging regime, the fires will grow till

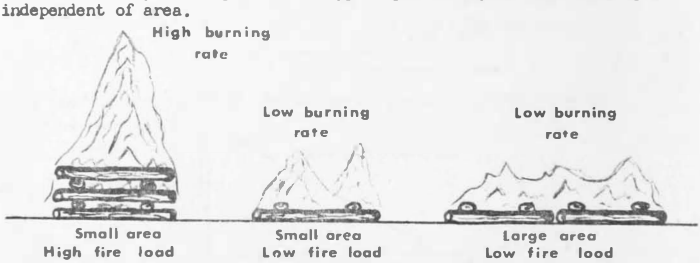
$F_2 = N^{1/2} \ (U + V) \ j$ is satisfied

In this case $b = N^{1/4} \ (U + V)^{5/2} \ \ (j/a)^{3/2}$

Thus N is proportional to F_2^2 and to b^4 and F_2 is proportional to b^2.

These proportionalities are still valid if F/L is any function of R^2/L.

8 Fire intensity for a given fuel type depends only on fire loading and is independent of area.



9 Scaling of energy requirements.

9a If all linear dimensions are to be doubled, then Power Needed increases by a factor of 8 and Burning rate/cm.^{2} of ground (R) increases by 2. If Pressure difference does not vary then pressure gradient decreases by 2 and since distance air is to be accelerated increases by 2 time needed to establish the airflow increases by 2. So minimum fire loading to establish the airflow increases by 4.

9b As in theory 9a, but let power needed increase by 2^n

Then R increases by 2^{n-2}

Time needed increases by 2

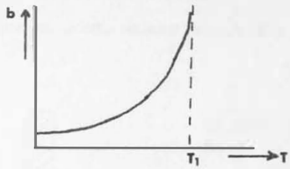
Minimum fire loading increases by 2^{n-1}

Table 1: Ratios of quantities in 2 scaled burns

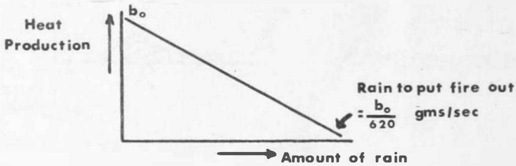
	Theory 9a	Theory 9b
Linear Dimensions	L	L
Power needed	L^3	L^n
Burning rate/cm^2	L	L^{n-2}
Pressure Difference	L^0	L^0
Pressure Gradient	L^{-1}	L^{-1}
Time needed	L	L
Minimum Fire Loading	L^2	L^{n-1}

Theories of Weather and Fuel

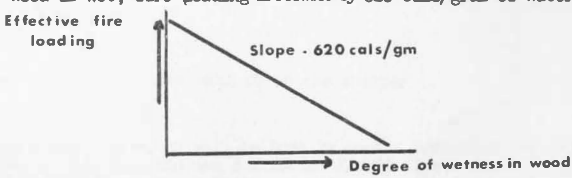
10 If initial temperature of wood = $T^{o}C$, and breakdown temperature = $T_1{}^{o}C$, Burning rate is inversely proportional to $(T_1 - T)$.



11 If rain falls during a burn, heat production is reduced by 620 cals per gram of water falling on a pile.



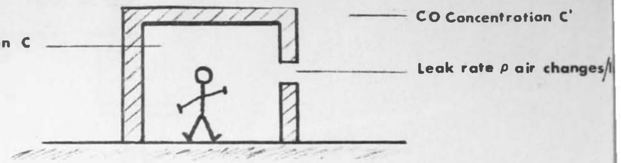
12 If wood is wet, fire loading is reduced by 620 cals/gram of water.



13 If inert material is mixed with the fuel it has no effect on the heat generation; count only fuel for the fire loading.

Theories of Shelter

14 Theories of toxic gas penetration.

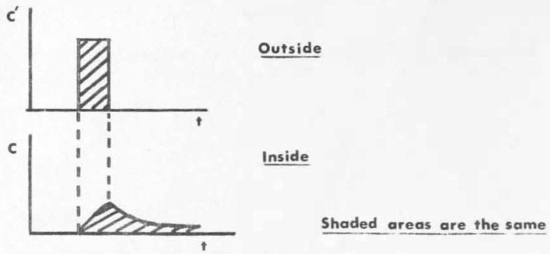


14a Let C be the internal concentration of CO, and C' that outside.

Then $\frac{dC}{dt} = p(C' - C)$

and if D is the time integral of C over the whole period, and D' the integral of C', then by integrating the differential equation over the whole period, D = D' (equal dose theorem)

Hence the shelter does no good, unless completely sealed (p = 0).



14b As in theory 14a

Put $\frac{dC}{dt} = pC' - qC - r$ (due to losses etc.)

Then $D = \frac{pD'}{q} - \frac{rt_2}{q}$

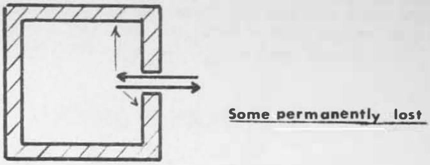
where t_2 = total time with CO in the shelter

As a special case, CO will be lost by people breathing it. Assume that between them they consume a fraction f/unit time.

therefore $\frac{dC}{dt} = p(C' - C) - fC$

therefore $q = p + f$, $r = 0$

therefore $D = \frac{pD'}{p+f}$



14c As in theory 14a, but dose is not the criterion of harm; there is a threshold concentration C_0. If this is reached at time t_1 in the shelter and ceases at time t_2.

$$D = \int_{t_1}^{t_2} (C - C_0)\, dt$$

$$= \int_{t_1}^{t_2} (C' - C_0)\, dt$$

Suppose that C' can be approximated by a constant value $Q\,C_0$ for a time E/p. Then before this time, $C = Q\,C_0\,(1 - e^{-pt})$

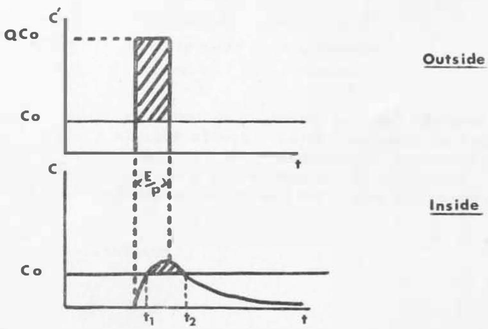
and after it $C = Q\,C_0\,(e^{E} - 1)\,e^{-pt}$

also $t_1 = \frac{1}{p} \log \frac{Q}{Q-1}$

and $t_2 = \frac{1}{p} \log \left(Q\,(e^{E}-1) \right)$

Finally, $D = D' \left(1 - \frac{1}{E} \log \frac{Q}{Q-1} - \frac{1}{EQ} \log \left\{ (Q-1)(e^{E}-1) \right\} \right)$

Note that $D = 0$ (perfect protection) when $E \leq \log \frac{Q}{Q-1}$



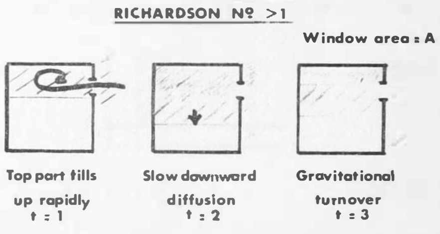
14d Gravity stratification - Rasbash (6)

Suppose gases enter the shelter through a window of area A with a speed W. The difference in density from the air in the shelter is $\Delta\rho$. Now if the window is at the bottom of the shelter there will be thorough turbulent mixing and theories 14a, b or c will apply; and also if the modified Richardson number $\frac{g}{W^2} A^{1/2} \frac{\Delta\rho}{\rho}$ is less than 0.1.

If it is more than 1, however, the gases in the shelter should be well stratified with the hot incoming gases lying on top. Assume the top part of the shelter fills up rapidly so that C = C'. The gases will then slowly diffuse downwards following the equation

$$\frac{\partial^2 C}{\partial z^2} = - \frac{1}{s} \frac{C}{t}$$

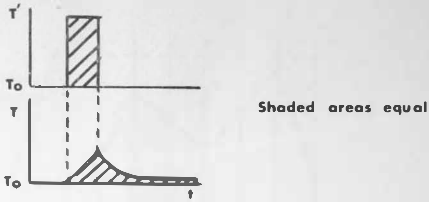
Where z is the vertical co-ordinate and s a diffusion coefficient. In the later stages, when C' starts dropping, assume that gravitational turnover will keep the maximum concentration down to C'.



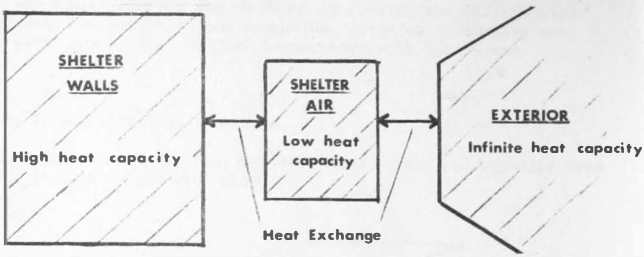
14e Assume there is "recovery" from CO poisoning so that the same dose over a longer time gives a smaller effect. If the recovery is linear this is equivalent to theory 14c; if it is exponential (proportional to dose) or any other relationship, the protection can be evaluated numerically, knowing the dependence of C' on time - see theory 20.

15 Theories of heat penetration.

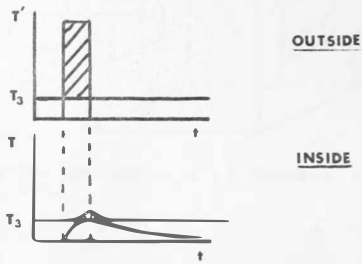
15a If there is a simple mixture of gases, then with ambient temperature T_0, $T-T_0$ corresponds to C in theory 14a. However, "Temperature Dose" is not the criterion of harm.



15b Allowing for the loss of heat to the shelter walls still leaves the mathematics of theory 14a valid. The constant p, however, is greatly reduced, by a factor $\frac{\text{heat capacity of air and walls}}{\text{heat capacity of air}}$.

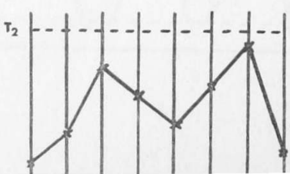


15c Taking heat stroke as the limiting factor, the risk of this may be measured by the integral of $T-T_3$, where T_3 is a critical temperature of about 32°C. The mathematics of theory 14c then follows.

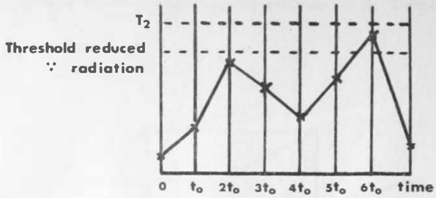


15d Skin burns occur when T is greater than T_2, which is perhaps 400°C. If the probability of T being greater than T_2 at a specified moment is P, then divide the total exposure time t_2 into effectively independent periods of duration t_0. The probability of a man getting burnt at any time during t is then:-

$$1 - \exp(-Pt_2/t_0)$$



15e In theory 15d, to allow for the combined effect of hot air and thermal radiation, let 1 cal/cm.^{2}/sec. be equivalent to K°C. T_2 can then be reduced by the appropriate amount.

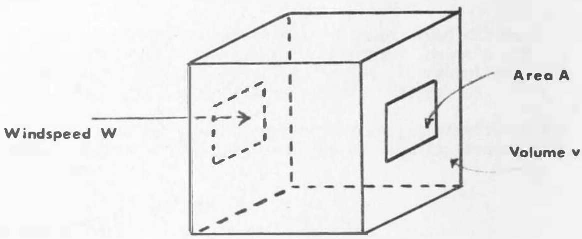


15f Straight conduction of heat through the walls is probably not very important. An exact solution can be found by solving the differential equation of heat conduction in one dimension, given as a boundary condition the variation of the external temperature with time - see theory 20.

16 Theories to calculate the leak rate.

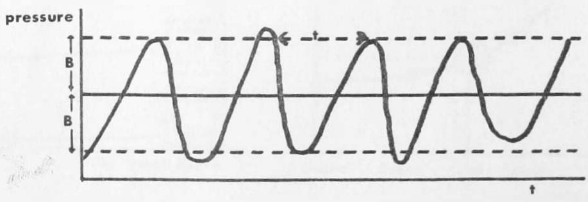
16a To calculate p in theory 14a, assume a room volume v,2 opposite open windows each of area A, and wind speed W.

Then $p_1 = AW/v$



16b If there are pressure fluctuations of ± B millibars, occurring with an average periodicity of t',

$$p_2 = \frac{B}{1000t'}$$

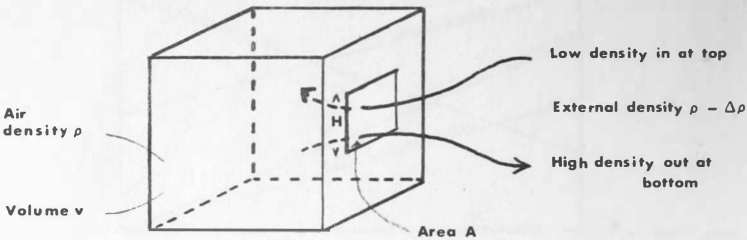


Assume B is a function of the average windspeed only.

16c Gravitational pumping - Heselden (7)

If the height of the window from top to bottom is H, then:-

$$p_3 = \frac{A}{v}\left(g\,H\,\frac{\Delta\rho}{\rho}\right)^{1/2}$$

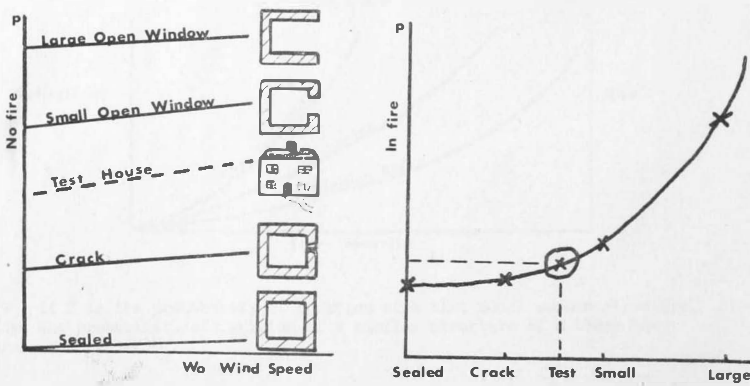


16d If there are wind, pressure and gravitational effects,

$$p = p_1 + p_2 + p_3$$

NOTE that the wind, pressure and gravitational effects would all tend to be strongest when the fire is burning most fiercely. Hence p may tend to drop in the later stages of the fire, leading to retention of low concentrations of CO for longer than expected by theory 14a.

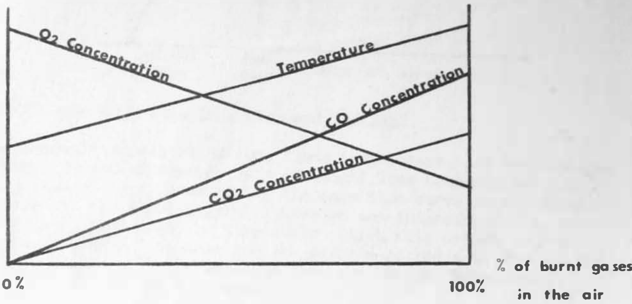
16e The graph of p against W_0 (with no fire) is a characteristic of the structure depending only on geometry, and can be used to predict the value of p with a fire.



Theories relating to measurements

17 Gas Composition and Temperature.

17a Air can be simply characterised by the proportion of burnt gases in it. Hence the temperature rise above ambient, the CO%, the CO_2%, and the drop in O_2% are all proportional to one another, and a measurement of any one will enable all the others to be calculated.



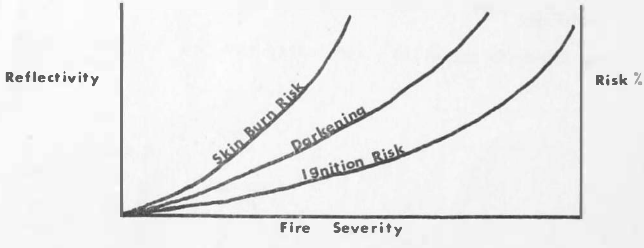
17b Theory 17a is only true for a given type of burning; when this changes, the ratios are upset.

18 Wood block instruments.

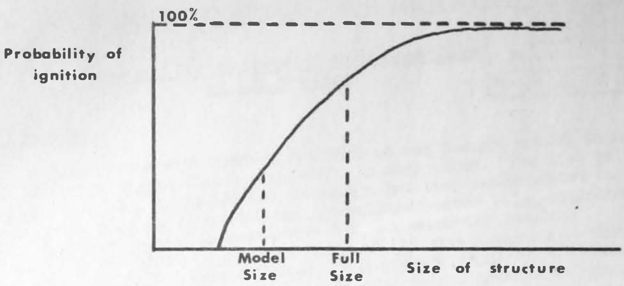
18a The degree of darkening (due to scorching) of a piece of white wood or fibre board exposed in a fire area is a measure of the overall severity of fire conditions at that point and is directly related to the probability of ignition of cellulosic materials.

18b The darkening is similarly related to the probability of skin burns.

18 a & b

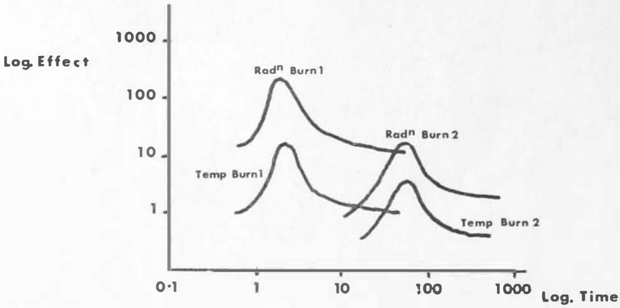


19 If P is the probability of ignition of a flat model wooden structure, then the probability of ignition of a similar structure of M times the area is: $1-(1-P)^M$

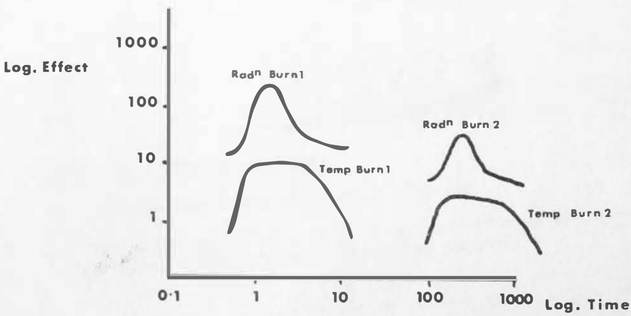


20 Fire effects vary with time in a standard fashion.

20a All fire effects (thermal radiation, flame temperature, air temperature, soil temperature, induced windspeed, rate of weight loss CO concentration, etc.) follow, on the average, identically the same time curve in all fires. This allows variations in a multiplying factor on the intensity scale, and also in a multiplying factor on the time scale (which will depend only on the burning rate, and so be the same for all effects in the same part of the same fire). All temperatures are measured from the initial temperature. The curves can be drawn on log:log paper.



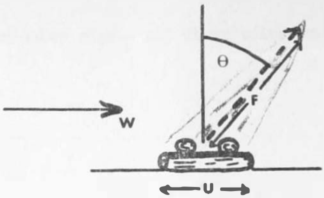
20b As in theory 20a, but each effect has a different characteristic shape of curve.



21 Flame height (or length) F and angle from vertical θ in a wind W with a burning rate b are given by:-

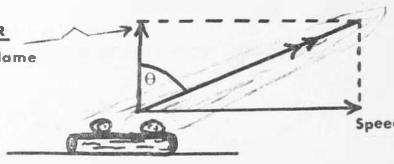
$$F = F(b,W)$$
$$\theta = \theta(b,W)$$

These equations can be solved for b and W, given measurements of F and θ



21a $F = a(UR)^{2/3} = a(b/U)^{2/3}$ as in theory 7b
i.e. F is not affected by W or θ

21b Measure R in mass units (gms lost/sec/horizontal sq. cm). Then gas must flow upwards with velocity R/ρ_{flame}, and sideways with velocity W. Hence $\tan\theta = W.\rho_{flame}/R$

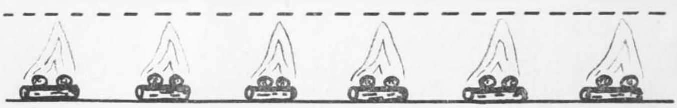


Mass burning rate R $gms/cm^2/sec$

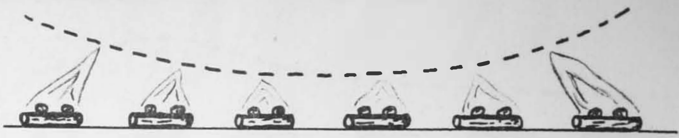
Simple tests of some of the theories

It should be fairly easy to investigate the variation of the burning rate or flame height with position in the array; some of the theories give quite different predictions on this:-

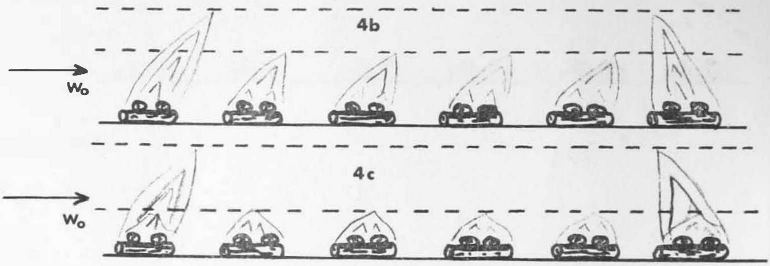
2a Same everywhere.



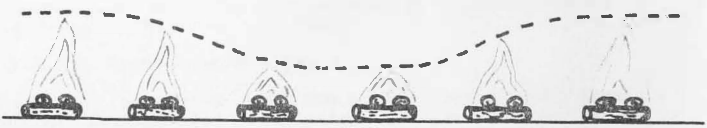
4a Maximum at or near edges falling steadily to minimum at centre - but may be modified by Wo



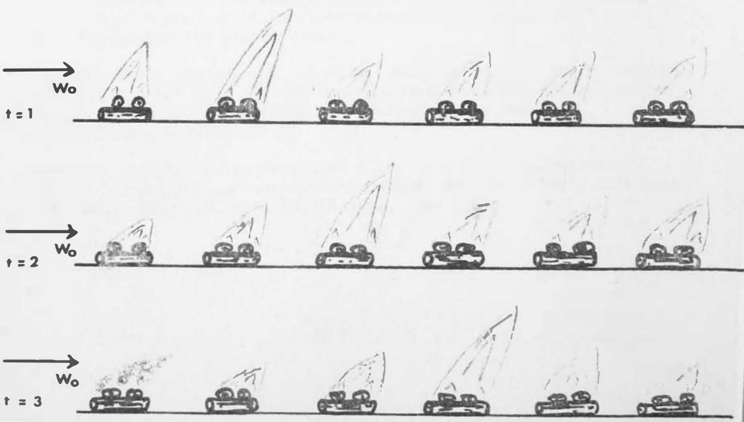
4b} High on outer edge - all other piles low and same as each other.
4c}



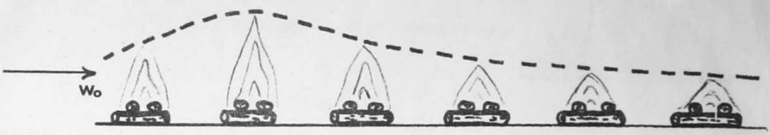
5a,5d,5e,5f All piles the same once well away from edges.



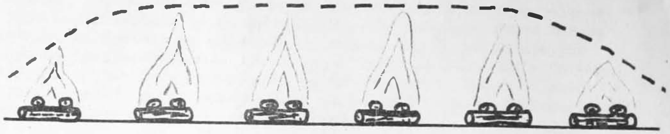
5b Progresses downwind through the array at constant speed - a wave motion.



5c Maximum some distance in from the upwind edge.



6 Low on outer edge - all other piles high and same as each other.



December 1966

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